Supernova Relic Neutrinos in Super-Kamiokande IV

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Super-Kamiokande

Super-Kamiokande (SK) is currently the largest pure water Cherenkov detector. It is located under a 1000 m mountain in the Kamioka mine (Japan). It consists of an Outer Detector (OD, muon veto), and an Inner Detector (ID). Its fiducial volume is 22.5 kton.

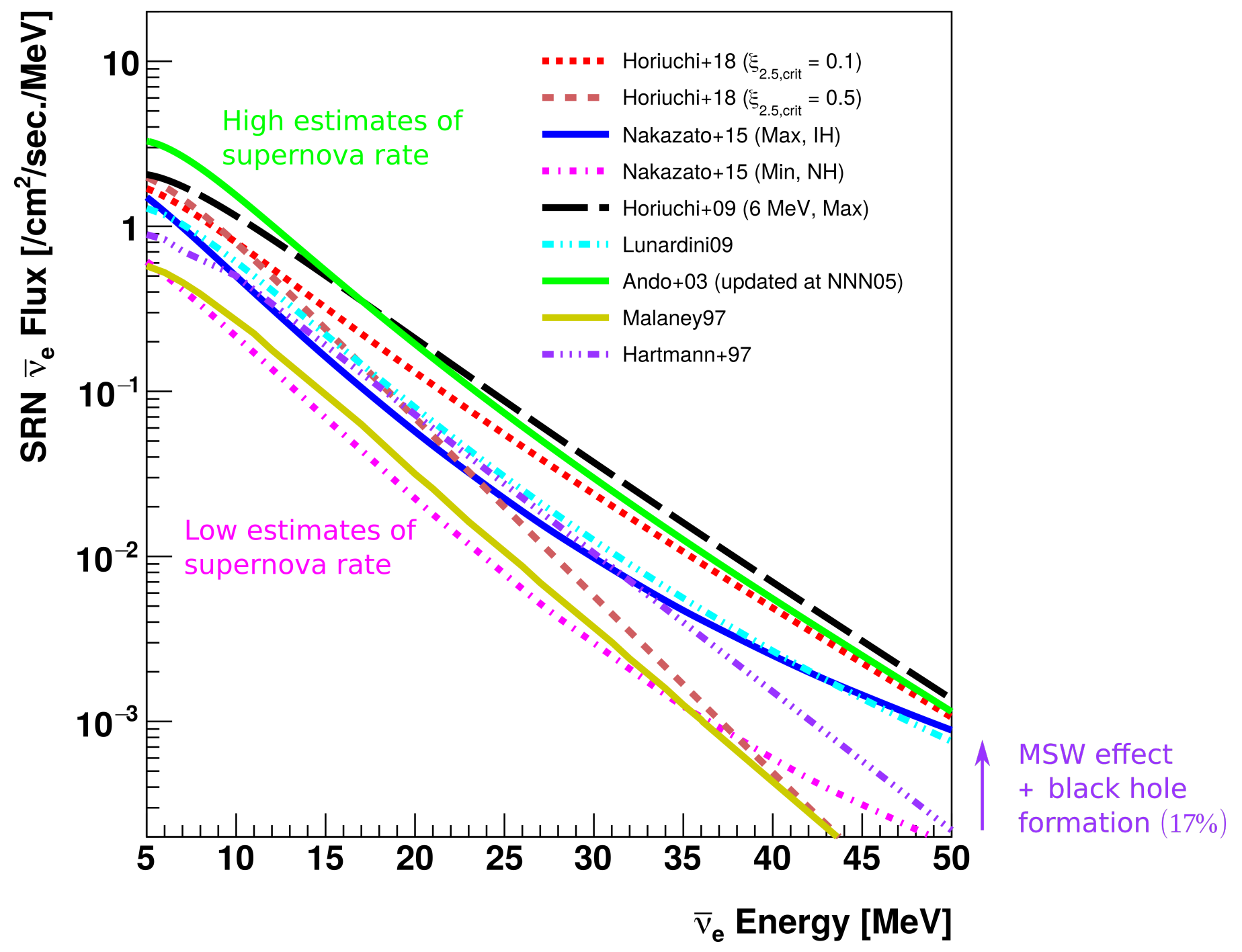
SK's inner detector contains 11146 photomultipliers (PMTs) with 3 ns time resolution. A typical event in SK lasts at most 200 ns. SK has gone through four phases of running. This analysis focuses on phase IV (2790 days).

Supernova relic neutrinos

Core-collapse supernovae emit about 10^{58} neutrinos that could provide unique information about the behavior of the core of heavy stars. Since about 1 supernova/second occurs in the Universe neutrinos from distant supernovae form a permanent, diffuse background. These Supernova Relic Neutrino (SRN) flux carries unique information about the aggregate properties of core-collapse supernovae as well as the history of the Universe:

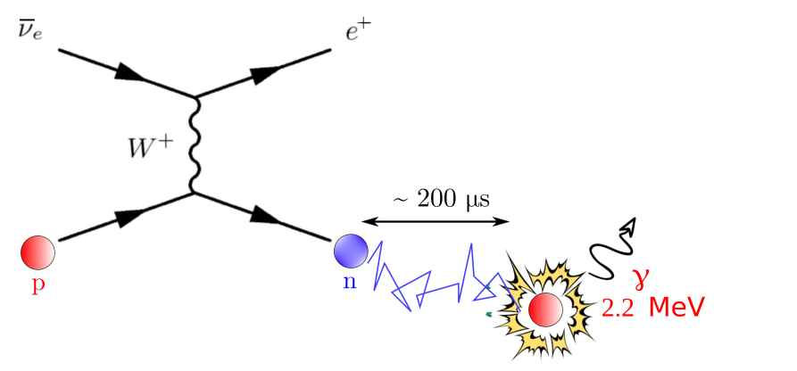
$$\Phi(E) = \frac{c}{H_0}\int_0^{z_{\max}} \frac{F_\nu[E(1+z)]R_{\rm SN}(z)}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}{\rm d}z$$
$$= \int \left[\begin{array}{c}\nu\\ \text{spectra}\\ \text{(black hole}\\ \text{fraction)}\end{array}\right] \otimes \left[\begin{array}{c}\text{Star for-}\\ \text{mation}\\ \text{history}\end{array}\right] \otimes \left[\begin{array}{c}\text{Universe}\\ \text{expan-}\\ \text{sion}\end{array}\right]$$

Flux predictions can vary over one order of magnitude depending on the assumed supernova rate R_{SN} and neutrino emission spectrum F_ν. For most models, 5 to 20 evts/year are expected in Super-Kamiokande. The figure below shows the fluxes associated to several representative models:



Measuring the SRNs would bring unique insight into supernova mechanisms, and is the only way to measure the formation rate of stellar black holes.

SRN signal and main backgrounds



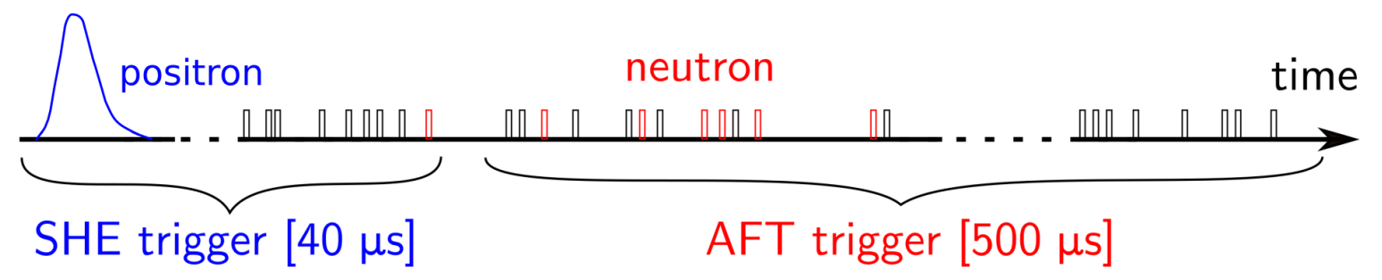
Inverse Beta Decay (IBD)

Positron: "prompt" signal
Neutron: captured by a proton
2.2 MeV γ "delayed" signal

Three main categories of backgrounds at these energies:

- **Cosmic muon spallation**: cosmic muons induce the production of radioactive isotopes, that later undergo beta decays. Most decays do not involve neutrons. One notable exception is ^{9}Li, that undergoes $\beta + n$ decay.
- **Solar neutrinos**: most of this background can be rejected using directional cuts. Again this background does not involve neutrons.
- **Atmospheric neutrinos**: neutral current (NC) interactions dominate over 12 MeV and produce energetic γs with sometimes a neutron. Charged current (CC) interactions mostly do not produce neutrons. The only irreducible backgrounds are $\bar{\nu}_e, \bar{\nu}_\mu$ IBDs.
- **Reactor antineutrinos**: irreducible background below 10 MeV

Analysis strategy



Search energy range: 12 to 90 MeV
10^5 events in SK-IV after basic noise cuts. Less than 100 could be SRN.

Modeling:
Atmospheric ν interactions are modeled using NEUT [4].
Detector simulation: SKDetSim (GEANT3) + noise injection (data).

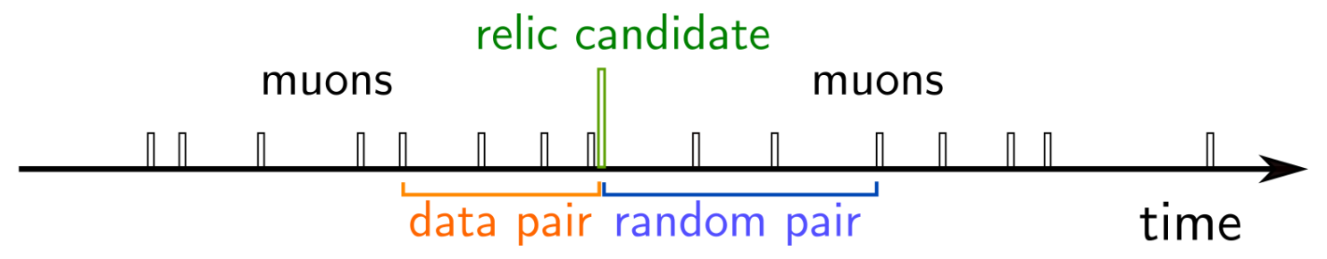
Identifying both the positron and the neutron is essential in the SRN search.

Cut strategy:

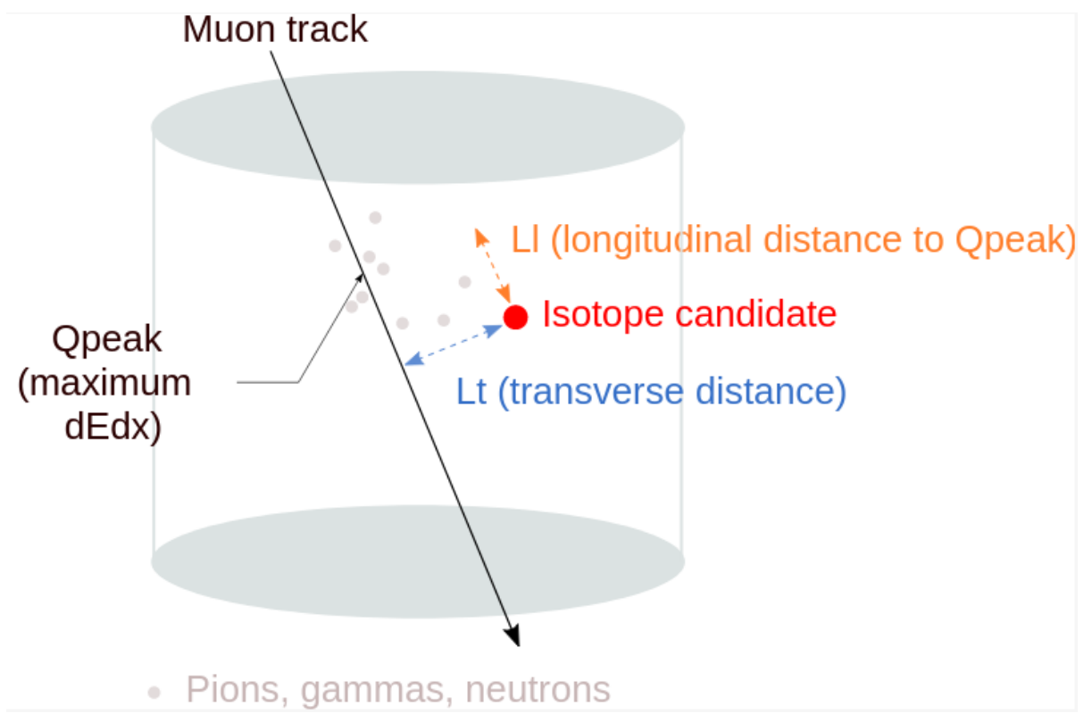
1. **Noise reduction**: basic cuts (radioactivity, PMT flashers, ...)
2. **Spallation cuts**: exploit space and time correlations between spallation events and cosmic muons. Remove > 90% of backgrounds.
3. **Atmospheric reduction**: remove pions and electrons from muon decays. > 90% signal efficiency, remove 20% of atmospheric background.
2. **Neutron tagging**: eliminates > 99.9% of the backgrounds at low energy. Low signal efficiency.

Spallation cuts

Study correlations between each SRN candidate and all muons detected up to 30s before ($\sim$ 50 pairs/event). We compare these pairs to uncorrelated "random" pairs (see below) to design a two-step cut strategy:



1. **Preselection**: clustered SRN candidates (multiple spallation cuts), and candidates close to neutrons produced by muon showers are rejected. These cuts have a > 98% efficiency and eliminate about half of the spallation events.
2. **Final cuts**: select SRN candidates based on the following four variables



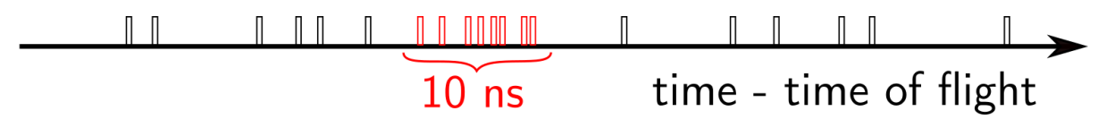
dt: time difference between candidate and muon
Ll, Lt: candidate's distance to shower
resQ: charge deposited by the muon minus minimum ionization

Final performance: > 90% of the background rejection ($\sim$ 99% of ^{9}Li), 40 to 90% signal efficiency (depending on positron energy).

Neutron tagging

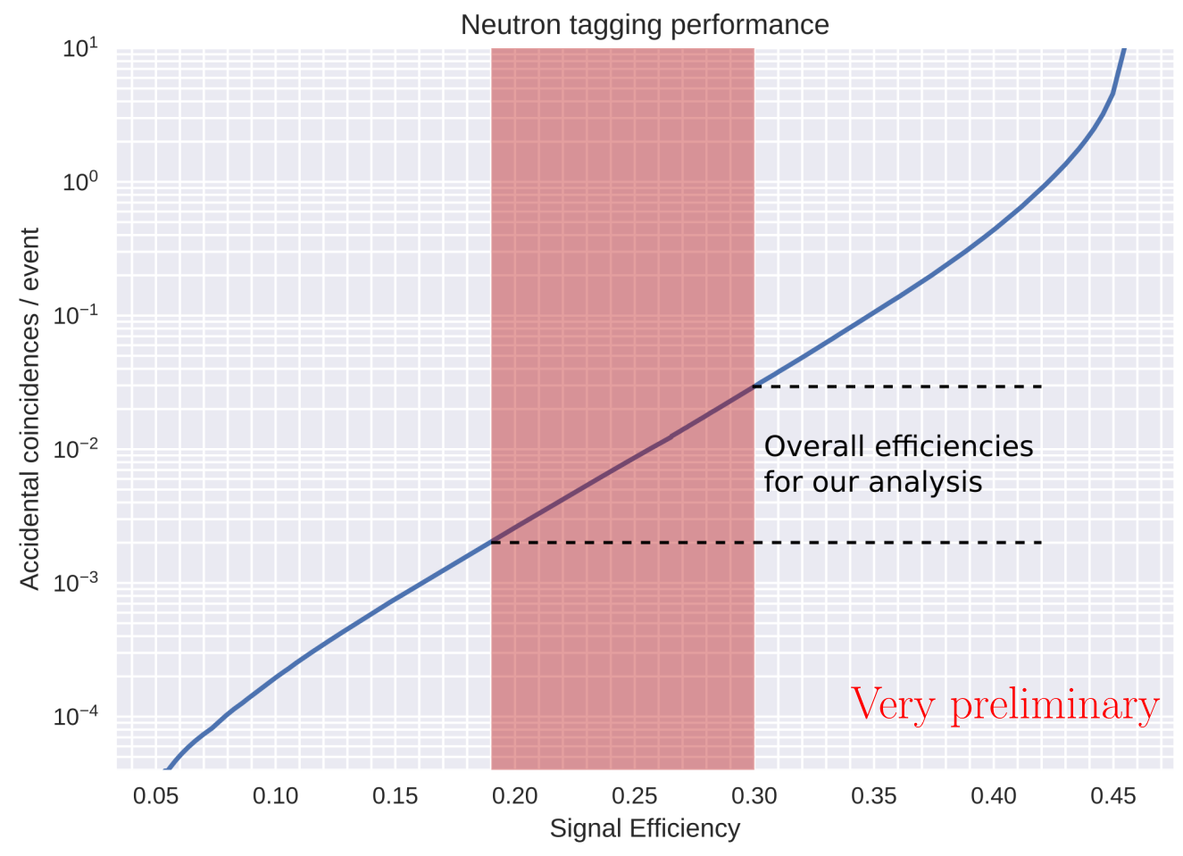
More than 99% of the backgrounds processes do not produce neutrons, which makes neutron tagging critical in this analysis. Distinguishing neutron captures from PMT noise however requires an extremely thorough search over a large time window [3].

1. **Preselection**: Identify the neutron capture vertex with the positron vertex and subtract time-of-flights. Select clusters with $\geq$ 6 hits in 10 ns

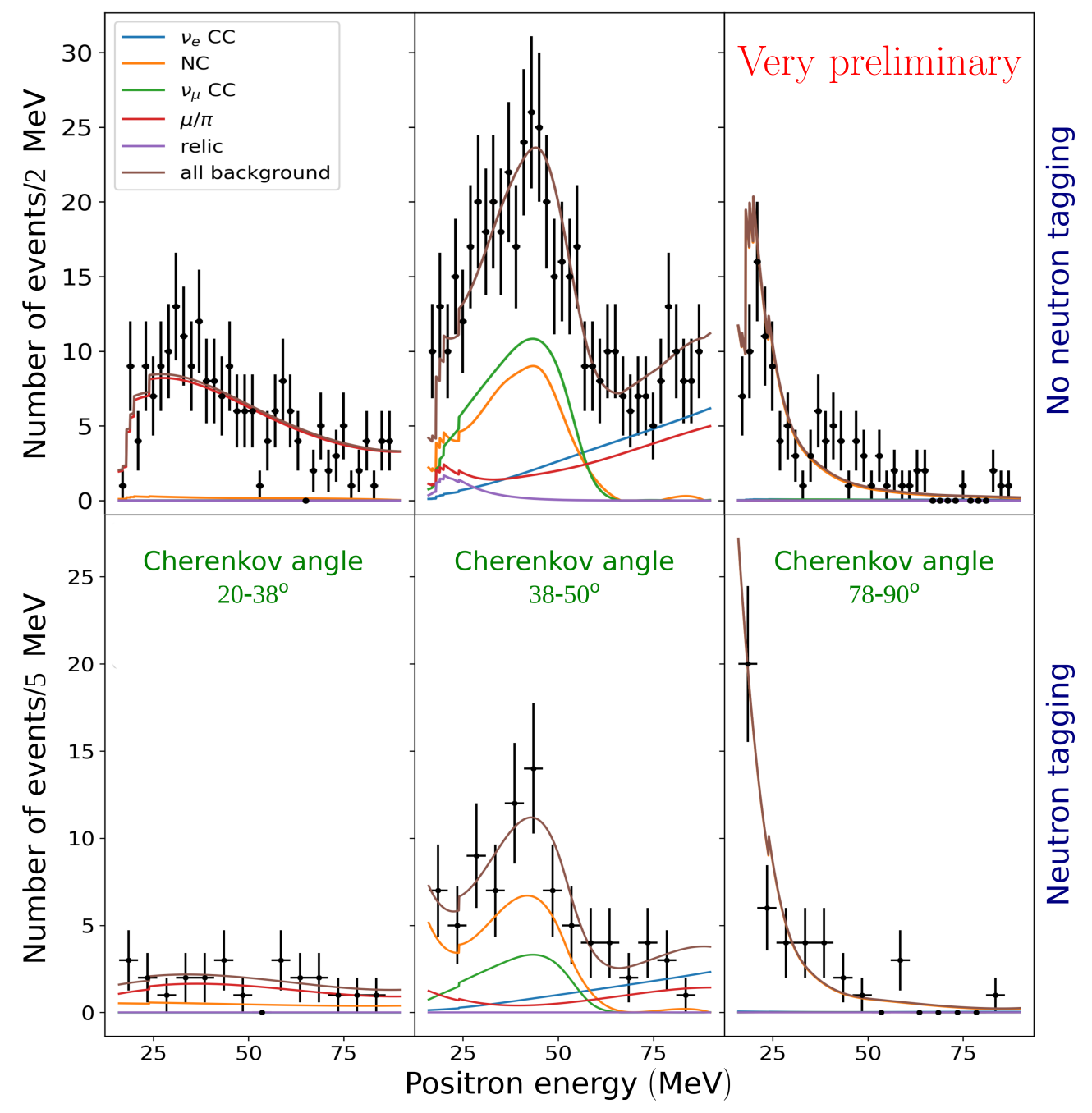


2. **Final selection**: use a Boosted Decision Tree (22 observables).

Overall efficiencies: 19-30% (signal), 0.2-3% (background).



Spectral fits: Ando (LMA) model



We fit the energy spectrum of the remaining SRN candidates with a linear combination of a SRN signal (LMA model [1]) and the background predictions in the 16-90 MeV region. Cuts are tuned to eliminate non-atmospheric backgrounds and atmospheric backgrounds are estimated using data-driven techniques [2]. We notably evaluate the impact of NC interactions and μ/π production by performing an extended maximum likelihood fit over three Cherenkov angle regions. We study two configurations:

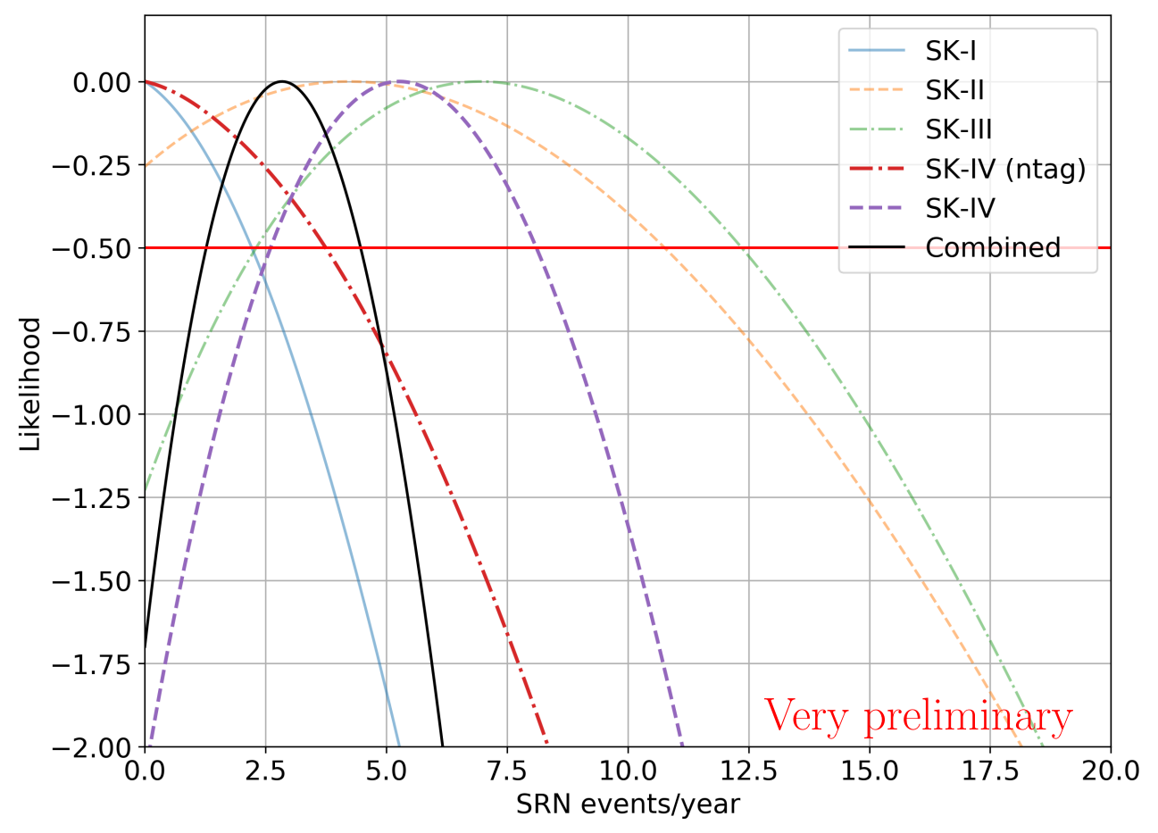
- No neutron tagging: signal efficiency for spallation cuts ranges from 37% (16-17 MeV) to 86% (20-24 MeV). We also apply solar cuts, whose efficiencies range from 73% to 95%.
- Neutron tagging: signal efficiency for spallation cuts is 88% for all energies. Neutron tagging efficiency is around 30%.

The 90% **preliminary** confidence limit on SRN flux for 22.5 × 2970.1 kton.day exposure is

$$\phi_{90} = 4.9\ \text{cm}^{-2}/\text{s (no neutron tagging)}, \quad 3.8\ \text{cm}^{-2}/\text{s (neutron tagging)}$$

Combining SK-IV results with SK-I,II,III (22.5 × 2853 kton.day) gives (**preliminary**):

$$\phi_{90} = 2.7\ \text{cm}^{-2}/\text{s (predicted 1.7)}$$

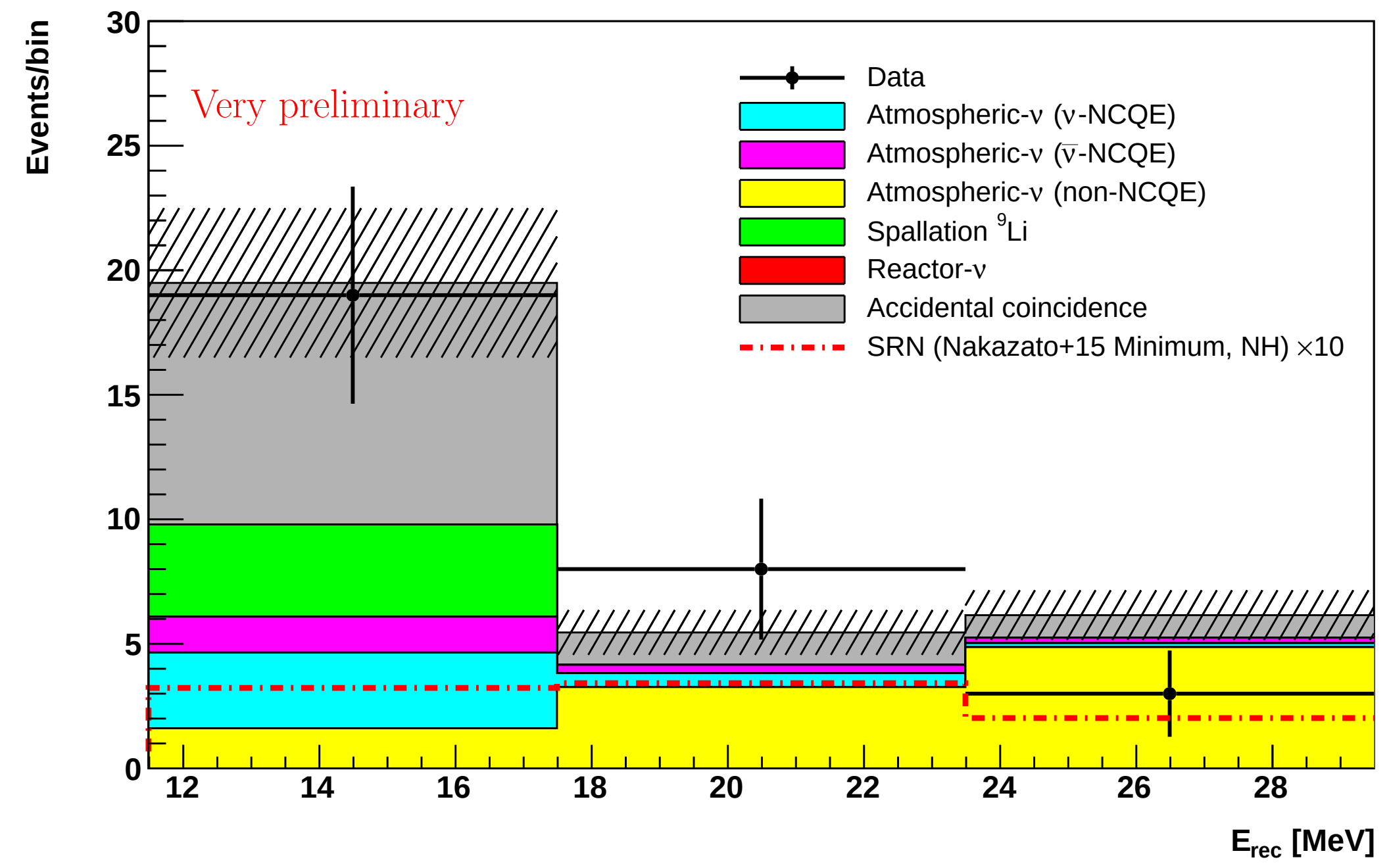


Exclusion limits

In addition to spectral fits, we compute supernova model-independent exclusion bounds on different positron energy bins in the 12 − 30 MeV region. Notable differences with the spectral analysis are:

- Joint optimization of spallation and neutron tagging cuts to maximize significance.
- Systematic errors on NC Quasi-Elastic (NCQE) backgrounds are evaluated using T2K data (and determine the energy bin size).
- The non-NCQE atmospheric backgrounds are estimated using the 30 − 80 MeV region as a sideband.

The data and background predictions after cuts are the following:



The resulting **preliminary** 90% C.L. flux limits for 22.5 × 2970.1 kton.day exposure are:

Search Results & Integrated SRN Electron Antineutrino Flux [/cm²/sec.]

E_ν region [MeV]	13.3–19.3	19.3–25.3	25.3–31.3
SK-IV 2970 days (Expected)	**9.48**	**1.35**	**0.82**
SK-IV 2970 days (Observed)	**9.08**	**2.22**	**0.35**
Horiuchi+18 ($\xi_{2.5,crit}$ = 0.1)	1.583	0.553	0.173
Horiuchi+18 ($\xi_{2.5,crit}$ = 0.5)	1.108	0.252	0.050
Nakazato+15 (Maximum, IH)	0.798	0.236	0.081
Nakazato+15 (Minimum, NH)	0.337	0.089	0.026
Horiuchi+09 (6 MeV, Maximum)	2.534	0.887	0.314
Lunardini09	1.032	0.321	0.098
Ando+03 (updated at NNN05)	2.652	0.796	0.261
Malaney97	0.469	0.125	0.034
Hartmann+97	0.947	0.297	0.093

Both the spectral and the supernova model-independent limits are within a factor of 2 of the Ando (LMA) model at high energies. Most SRN models will hence be within reach of the upcoming Super-K Gd!

References

1. Ando *et al.* (2003), *Astropart. Phys.*, **18**:307.
2. Bays *et al.* (2012), *Phys. Rev. D*, **85**:052007.
3. Zhang *et al.* (2015), *Astropart. Phys.*, **60**:41.
4. Hayato (2009), *Acta Phys. Polon. B*, **40**:2477.